LOW PRESSURE SPARK GAP

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Abstract

Tests of an experimental low pressure spark gap Blumlein switch are presented. Gas flows from a pulsed valve into the gap at a steady rate through holes in the cathode and results in a steady pressure of about 0.1 Torr. The pressure outside the gap over the Blumelin insulator is much lower. Trigger electrodes are mounted in the grounded cathode. Initially the current rises exponentially with time with rate constant proportional to gas density. Measurements of rise time, jitter and voltage holding recovery time are presented for charge voltages up to 250 kV for variations of charge time, gas density, gas type and triggering method.

I. Introduction

Several switch concepts are being tested as possible replacements for the high pressure spark gaps currently used on the ETA/ATA accelerators.[1,2] A low pressure spark gap might be expected to have fast recovery of voltage holding ability because the ionization will rapidly reach the electrodes and recombine. To be acceptable for our purposes, the triggered switch should have a fast rise time of the current ($\leq$ 20 ns), and a low jitter (width of the distribution of firing time delays < a few ns).

II. Apparatus

Figure 1 shows the apparatus as originally set up. The cathode (grounded electrode) is mounted on a metal tube of about 15 cm diameter. The vertical position of the cathode is adjustable by sliding the support tube in the seal in the 50 cm diameter plate that mounts on the bottom of the vacuum chamber. The cathode is 10 cm in diameter. The anode is a replaceable metal disc of about 15 cm diameter mounted on a projection of the high voltage electrode of the water Blumlein. An insulator with an outer diameter about equal to that of the outermost wall of the Blumlein supports the high voltage electrode and forms the interface between the water and vacuum.

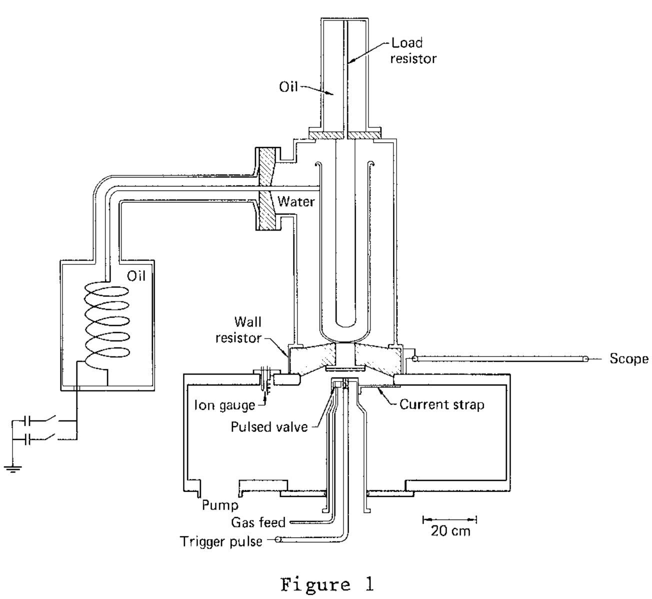

Figure 1
Low Pressure Switch Apparatus

The water Blumlein, the transformer for charging it and the thyratron-switched capacitor chassis for pulsing the primary of the transformer are copies of the ones developed for the ETA accelerator. The characteristic impedance of the lines is Z_o = 5.4 ohm and the series load resistor has a resistance of $2Z_o$ = 10.8 ohm. With an ideal switch which instantly changed from infinite impedance to zero impedance, the switch current would be a rectangular pulse of 49 ns duration with amplitude given by

$$I_o = \frac{V_o}{Z_o} \tag{1}$$

where V_o is the charge voltage of the lines.

The time dependent current in the spark gap is measured by measuring the IR voltage across a resistor in series with the Blumlein outer wall. The resistor is a 1.27×10^{-3} cm thick stainless steel foil wrapped around the edge of the insulator. the foil is 6.99 cm long and 139 cm in circumference and has a resistance of 10 volt/3000 A. It has subnanosecond time resolution.

Eight copper straps connect the cathode holder to the chamber near the edge of the insulator to minimize the inductance around the switch.

A novel feature of these experiments is that the gas density is not uniform in space but is largest in the electrode gap and is much lower over the surface of the insulator.[3] This allows a larger E-field than would otherwise be possible. We use electrode gaps of d = 0.5 to 4 cm. The tangential distance over the vacuum surface of the insulator is d_i 10 cm. In order to maximize the rate of buildup of current in triggered breakdown, one uses the maximum gas density which does not result in self-breakdown (prefire). Since the threshold condition for self-breakdown occurs at a critical value of the product, gas density x gap distance,[4,5] (i.e., a critical value of Pd where P is the gas pressure at constant temperature), the maximum P can only be attained in the gap without breakdown near the surface of the insulator if the pressure near the surface of the insulator is less than (d/d_i) times that in the gap. With N_2 or Ar, the maximum Pd is about 0.1 Torr cm. The non-uniform gas density is attained by admitting gas through holes in the grounded electrode. The flow of gas is controlled by a pulsed gas valve. In a typical case the valve is open for about 8 msec. When the valve opens, the flow between the electrodes adjusts to a time-steady state in a time < 1 msec. The gas diffuses to the outer edge of the cathode and then enters a large holding volume. While the valve is open, the pressure in the holding volume rises at a constant rate but makes a negligible contribution to the pressure in the gap. While the gap density is constant in time, a burst of pulses is fired.

After the valve closes, a 15 cm diameter diffusion pump pumps the 520ℓ holding volume down with about a 0.5 sec e-fold time constant. In order to interpret the measurements it is necessary to know the gas density at the position of the spark. Since it is difficult to measure the gas density in the gap directly, we measure the steady state flow rate and calculate the gas density. The flow is measured by measuring the rate of rise of pressure in the holding volume and multiplying by the volume. The time dependent gas pressure in the holding volume is measured with a nude ion gauge and fast transient control box.

Report Documentation Page			*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED
JUN 1981	**N/A**	**-**

4. TITLE AND SUBTITLE	5a. CONTRACT NUMBER
Cur Low Pressure Spark Gap	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **University of California, Lawrence Livermore National Laboratory, Livermore, CA 94550**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES
See also ADM002371. 2013 IEEE Pulsed Power Conference, Digest of Technical Papers 1976-2013, and Abstracts of the 2013 IEEE International Conference on Plasma Science. Held in San Francisco, CA on 16-21 June 2013. U.S. Government or Federal Purpose Rights License.

14. ABSTRACT
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15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			
unclassified	**unclassified**	**unclassified**	**SAR**	**4**	

One or several trigger electrodes are located in the cathode. Figure 2 shows a single trigger cathode. The upper picture is with the cathode cover plate removed to give a better view of the trigger electrode and its alumina insulator. The gas flows around the edge of the insulator and into the gap through the hole in the cover plate. Figure 3 shows views of a six-trigger cathode. The gas enters the gap through an axially symmetric crack at about 1.3 cm radius. Each trigger is driven by a separate identical length (58 ns) 50 ohm cable. Figure 4 shows a large 12 trigger cathode. The gas enters through a crack around each trigger. Approximately 20 kV pulses are used on the trigger cables, and the trigger gaps break down at < 5 kV.

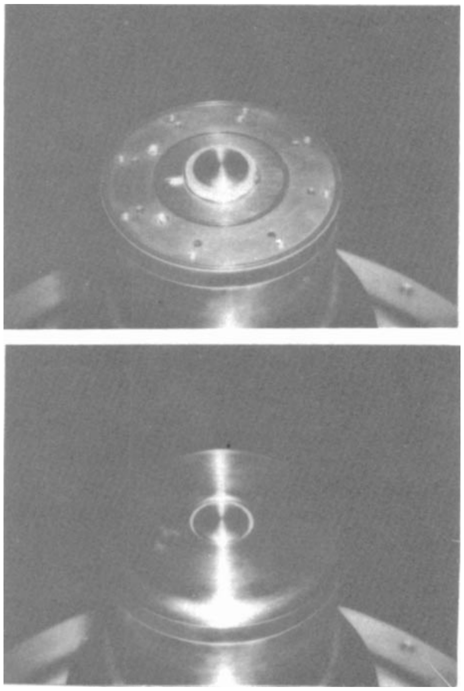


Fig. 2. 10 cm diameter, single trigger cathode.

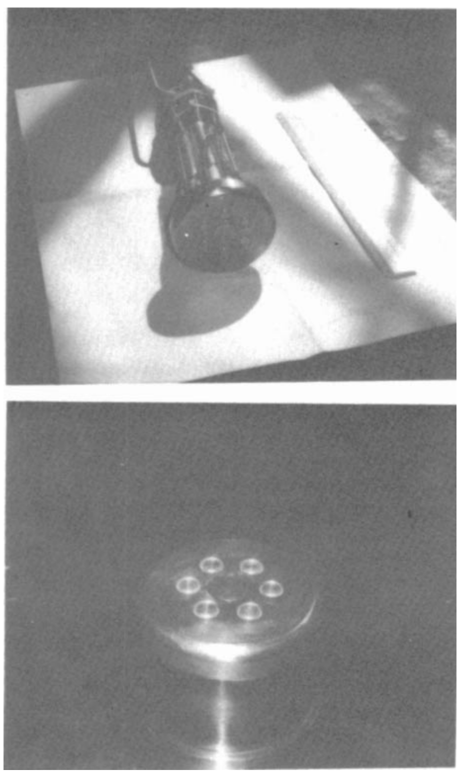


Fig. 3. 10 cm diameter, 6 trigger cathode.

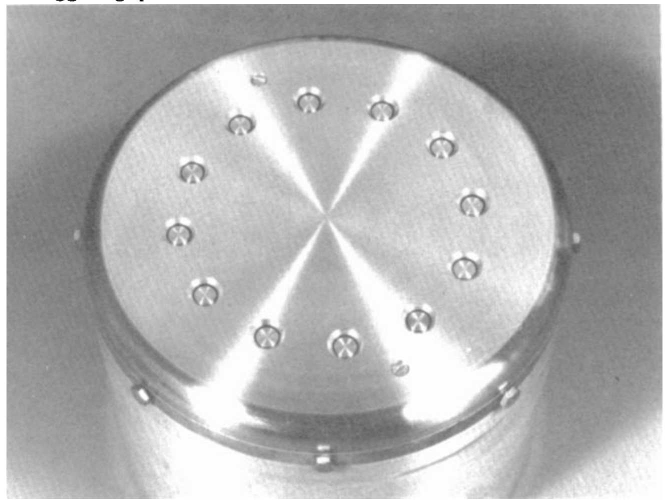


Fig. 4. 25 cm dia., 12-trigger cathode

The maximum Pd which does not result in self-breakdown (prefire) increases as the electrode charging time decreases. With the first charging circuit used (shown in fig. 1) the transformer charged the Blumlein directly. With the original ETA transformer mode, the voltage first oscillated negative and then positive, and the charging time was about 20 μs. The transformer was modified to first swing positive, resulting in a charging time of about 8 μs. Figure 5 shows the circuit now in use in which a two stage saturating magnetic modulator is placed between the transformer and Blumlein. This arrangement charges the Blumelin to 250 kV in about 0.2 μs.

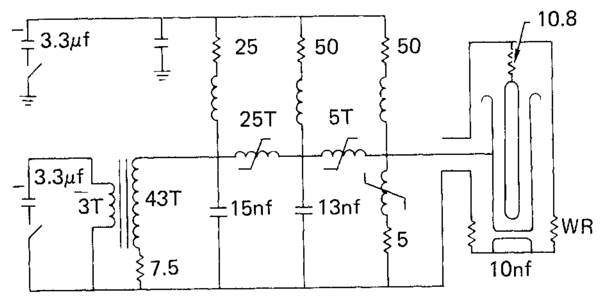
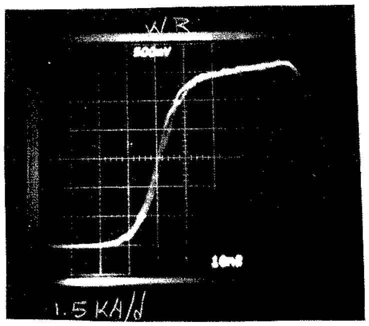


Fig. 5. Magnetic modulator Blumlein charging circuit

III. Current Rate of Rise and Jitter

Figures 6 and 7 show examples of satisfactory rise time and jitter with the transformer charging the Blumlein directly. With d and V_0 held constant, the current rate-of-rise increased in order of increasing molecular mass for the molecules H_2, D_2, He, N_2 Ar, Kr and Xe. The traces are five pulse overlays, and the jitter is seen to be negligible. With this "slow" charging mode, for $V_0 > 100$ kV it was necessary to use $d > 1$ cm. Because the prefire critical Pd is approximately constant, P had to be decreased and then the rise time was unacceptably long.

Figure 8 shows optimum performance using the "fast" charging mode. The self-breakdown critical Pd is about three times larger with the "fast" charging mode than with the "slow." So, for constant d, the pressure can be three times larger with the result that the exponential rate-of-rise of current is three times larger. Operation using 12 triggers is compared with operation with alternate trigger cables disconnected. Rise time and jitter were not affected.



10 ns/d

Fig. 6. Current vs. time, d = 0.5 cm, V_o = 50 kV, 10 cm diameter 6-trigger cathode, .086 Torr Ar

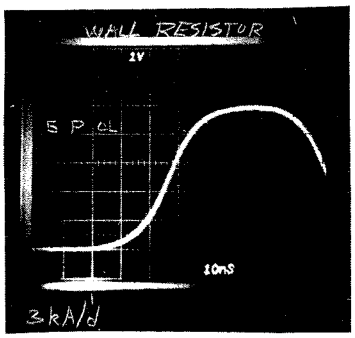


Fig. 7. Current vs time, d = 1 cm, V_o = 80 kV, 10 cm diam., 6-trigger cathode, Xe.

Figure 9 presents semi-log plots of current measurements vs time. The six-trigger cathode was used with 1, 3 or 6 triggers driven. There appears to be a small initial value of the current I(0) which increases with increasing number of triggers. Thereafter the current rises exponentially with time with a time constant characteristic of the gas and independent of the triggers--apparently until the gap voltage starts to decrease significantly. The apparent shift in horizontal position of the three curves is to be ignored, it is due to a change in the difference in time delays for sweep start and trigger gap breakdown as the number of driven cables is changed.

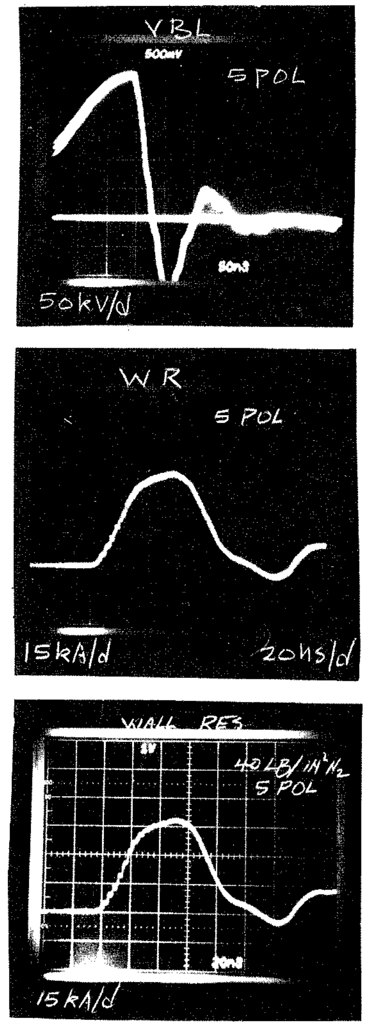
Semi-log plots of current vs time were made for a variety of conditions. The initial buildup is well characterized by the function

$$I(t) = I(0)\, e^{\nu t}. \qquad (2)$$

where ν is a function of the gas molecules used and varies linearly with the gas density and also depends somewhat upon d and V_o.

A simple numerical model has been used to predict the current buildup. The model assumes that the role of the trigger spark is to create a plasma near the cathode which is an unlimited source of electrons. Then the numerical calculation alternates between calculations I and II below. Calculation I solves a one-dimensional steady state Child-Langmuir type space charge limited electron flow problem using Poisson's equation

$$-\frac{\partial^2 V}{\partial x^2} = 4\pi e \left(n_i(x) - n_e(x)\right) \qquad (3)$$



50 ns/d

20 ns/d
N = 12

20 ns/d
N = 6

Fig. 8. Top trace: charge voltage, lower trace: current, d = 4 cm, V_o = 250 kV, 25 cm diam, cathode, N_2.

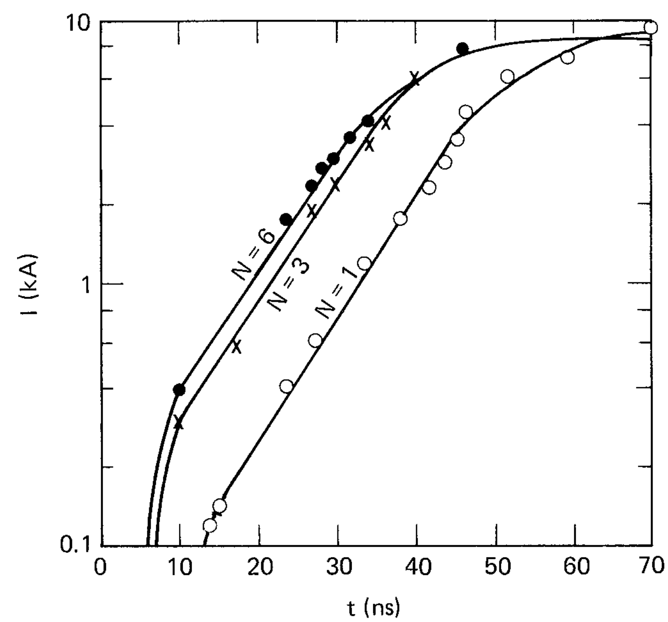


Fig. 9 Semi-log plot of I vst, d = 1 cm, V_o = 50 kV, .046 torr argon, with N = 1, 3 and 6 triggers.

where V is the self-consistent electrical potential, $n_i(x)$ is the positive ion density and $n_e(x)$ is the electron density. The conservation equation for n_e with $\partial n_e/\partial t = 0$ gives

$$J = n_e(x)\ v(x) = \text{const.} \tag{4}$$

where J is the electron current density in cm^{-2} sec^{-1} and v(x) is the electron velocity. The electron velocity is calculated from

$$\frac{1}{2}\, mv^2(x) = eV(x) \tag{5}$$

which neglects the loss of kinetic energy due to collisions. Also $V = 0$, $\partial V/\partial x = 0$ at $x = 0$ and $V = V_d$ at $x = d$. The problem is started at time zero with $n_i(x) = 0$. After solving problem I, the result for J is used in II to calculate a contribution to $n_i(x)$ during the time t using

$$\frac{\partial n_i}{\partial t} = n_g J\sigma\left(v(x)\right) \tag{6}$$

where n_g is the gas density and σ is the ionization cross section. Using the new cumulated $n_i(x)$ we return to I and calculate a new J etc. The calculation neglects ion motion and the contribution by electrons produced in the gap to the ionziation and to J. After a short transient phase, the calculated J builds up exponentially with time.

Figure 10 presents predicted and measured values of ν for argon. In argon the measured and predicted values of ν agree within 30%. In H_2 the measured is smaller than predicted. This may be because the assumption of infinite ion containment time is inadequate for the relatively small H_2^+ mass. Since we predict and observe exponential buildup of current and can predict the rate constant within 30%, it appears that we understand the basic mechanism of the low pressure switch.

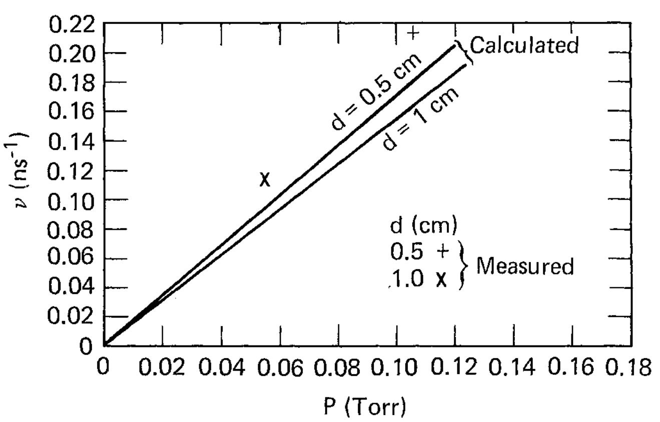


Fig. 10 Exponential rate of rise of current vs gas pressure (at 25°C), argon, 50 kV.

IV. Anode Damage

In the first tests using the single channel cathode, severe damage occurred on the anode surface for charge voltages greater than 100 kV. The original anode plate was stainless steel, and the surface appeared to be melted in localized regions of typically millimeter size. We changed to anode plates of copper with an arc deposited tungsten surface about .03 in. thick, and these suffer less damage.

The original single channel cathode was replaced with the 10 cm diameter, 6 channel cathode. Unacceptable damage to the anode still occurred. Visually it appeared that although several channels were initiated from the cathode a single, narrow hot spot occured on the anode. Apparently, energetic electron beams are formed at about the time when the current has risen to $V_o/2\ Z_o$ and the voltage has fallen to $V_o/2$. Magnetic pinching caused the six beams starting from the cathode to focus to a single spot on the anode.

Finally we changed to the 25 cm diameter cathode with twelve triggers located on a 15 cm diameter circle. Damage now appears to be minimal for d = 4 cm and V_o = 250 kV.

V. Minimum Time for Recovery of Voltage Holding Ability

With the original "slow" charging mode and V_o = 50 to 100 kV and N_2 gas, recovery times of 0.1 to 0.2 ms were observed. Since changing to the "fast" charging mode, the minimum recovery time has been several ms, apparently because of the negative voltage applied to the gap by the reset pulses for the saturating magnetic cores. We expect to correct this problem in further tests.

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Acknowledgment

The Lawrence Livermore National Laboratory is operated by the University of California for the Department of energy under Contract No. W-7405-Eng-48.

This work is performed by LLNL for the Department of Defense under DARPA (DoD) ARPA Order 3718, Amendment #33 and 34, monitored by NSWC under Contract No. N60921-81-LT-W0009, Amendment No. 1 and N60921-81-LT-W0026.